Technical feasibility study of scroll-type rotary gasoline engine: a compact and efficient small-scale Humphrey cycle engine

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HIGHLIGHTS

- A novel scroll-type rotary engine using Humphrey cycle was proposed and studied
- Evaluation of energy and exergy efficiency were conducted
- Performance and fuel consumption of a small scale system were investigated

Abstract

This paper reports the study of a conceptual gasoline Internal Combustion Engine (ICE) using scroll type rotary device rather than conventional piston as the main engine component. The proposed innovation engine adopts Humphrey Cycle to maximise the power performance of ICE. A performance comparison of the Humphrey Cycle, Otto cycle and Brayton cycle has been conducted and studied. The effects of using different designed compression ratio under variable expansion ratio have been investigated, which identify the optimal operational conditions under different compression/expansion ratio of the engine. Optimal performance can be achieved under the compression/expansion ratio at 2:1/4.8:1, 4:1/7.4:1, 6:1/9.9:1, 8:1/11.8:1 and 10:1/14.1:1, when the energy efficiency of the system can be respectively achieved at 42.22 %, 49.13 %, 52.82 %, 55.08 % and 56.96 %. A case study has been conducted to study the performance of small-scale scroll-type

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rotary ICE. Results pointed out under designed compression ratio from 2:1 to 10:1 the effective power from the system ranges from 3.343 to 19.01 kW. The analysis of fuel efficiency pointed out the Brake Specific Fuel Efficiency (BSFC) of the scroll-type rotary engine burning gasoline ranges from 130.5 to 148.5 g/kWh, which improve the fuel efficiency by 28.02 % and 65.89 % compared to that of the conventional gasoline engine.

Keywords: Scroll rotary device, First and second law analysis, Humphrey cycle, Internal Combustion Engine, Efficient and compact system

Nomenclature

$\dot{E}$	Exergy flow per unit time (kW)
h	Specific enthalpy (kJ/kg)
$\dot{m}$	Mass flow rate (kg/s)
M	Molecular mass (g/mol)
N	Rotational speed (rpm)
P	Pressure (kPa)
$\dot{Q}$	Rate of heat flow (kW)
s	Specific entropy (kJ/kg·K)
T	Temperature (°C)
v	Specific volume (m^3/kg)
$\dot{W}$	Power (kW)

Greek letters

$\eta_{I\_scroll\_ICE}$	First law efficiency
$\eta_{II\_scroll\_ICE}$	Second law efficiency
θ	Crank angle between the fixed scroll and orbiting scroll
$\gamma_{\_\mathrm{com}}$	built-in compression volume ratio of the scroll-type engine
$\gamma_{\_\mathrm{exp}}$	Built-in expansion volume ratio of the scroll-type engine
x	Mass fraction

Subscripts

com	Compression process
combustion	Combustion process
d	Geometric designed point
exp	Expansion process
ise	Isentropic
iso	Isochoric

Acronyms

BSFC	Brake specific fuel consumption (g/kWh)
ICE	Internal Combustion Engine

1. Introduction

1.1 Demand for high efficient combustion cycles

For over 100 years the conventional Internal Combustion Engine (ICE) has only 33% efficient and it is extremely difficult to improve the overall energy efficiency of the ICE because all aspects of ICE are almost operated under the best conditions [1]. The two most well-known ICE technologies are gasoline engine and diesel engine, which respectively adopts Otto cycle and Diesel cycle. The increasing concerns on the environmental problems caused by burning fossil fuels promote the technology development of more efficient, more compact and more cost-effective ICE, which can potentially improve the overall energy efficiency, reduce the emissions compared with the conventional engine and generate more effective engine shaft power by burning fossil fuels.

1.1.1 Constant volume combustion cycles-Otto and Miller

The compression stroke of the Otto cycle equals to the expansion stroke, which means the in-cylinder pressure at the end of the expansion is much higher than the atmospheric pressure. There is still considerable energy to make useful work at the end of the expansion process. The study of Miller cycle was proposed by Miller [2] with the purpose of improving engine efficiency. The Miller cycle adopts overexpansion, which has an expansion ratio higher than its compression ratio [3]. A real Miller cycle generally left the intake valve open longer than it would be in an Otto cycle engine [4]. Wang et al. [5] concluded the application of Miller cycle on petrol engine can reduce the engine exhaust gas emissions and significant NO_x reduction could be achieved with a penalty in engine fuel consumption. Mikalson et al. [3] investigated the potential of using Miller cycle natural gas engine as a domestic combined heat and power system. They concluded the Miller cycle engine has a potential for improved fuel efficiency but at the cost of a reduced power to weight ratio [3].

1.1.2 Constant pressure combustion cycles-Diesel and Brayton

The main difference between Diesel and Otto cycles is the combustion process, where Diesel cycle adopts constant pressure combustion and Otto cycle utilises constant volume combustion [6]. Under the same designed compression ratio, the efficiency of Otto cycle is higher than that of Diesel cycle. And high compression ratio is always desirable, because the higher of the engine compression ratio, the higher the overall efficiency of the ICE can be achieved. However, the typical compression ratio of gasoline engine ranges from 7:1 to 10:1, which is much lower than that of the typical diesel engine. The reason is that in the Otto cycle engine an air-fuel mixture is compressed and detonation becomes a serious problem if too high a compression ratio is used [6]. Diesel engine does not have this problem because only air is compressed during the compression process. Gas turbine engine adopting Brayton cycle is playing a pivotal role in power generation and transportation technology during the past seventy years [7, 8]. Under the same operational conditions, the gas turbine engine using the same combustion process as the diesel engine can perform full expansion process, which can produce much higher power than diesel engine [9-11]. The industrial gas turbine can be particularly efficient if the waste heat from the turbine can be recovered by a heat recovery system to form a combined cycle [12]. The majority use of gas turbine technology is for large-scale application due to the limited manufactures and other technical issues. Small-scale gas turbine systems have many promising advantages over reciprocating engines (Otto or Diesel engines), such as higher power-to-weight ratio, relatively low emissions and very compact with only one moving part [13].

1.1.3 Full expansion cycle- Atkinson (piston) or Humphrey (gas turbine)

Fig.1 shows the P-V diagram of the full expansion cycle. Under the same compression ratio, the work for full expansion cycle can be higher than that of Brayton and Otto cycles as illustrated in Fig. 1. The application of full expansion cycle was first proposed in the piston-type engine to further improve the engine efficiency and potentially reduce the emissions. However, the reality of using full expansion cycle by the piston-type engine cannot be achieved. Similar as the concept of Miller cycle, which recovers the energy from the in-cylinder high pressure of Otto cycle, the full expansion cycle generally means all of the in-cylinder pressure is recovered through full expansion to the atmospheric pressure. The British engineer James Atkinson invented a piston-type engine with the potential to achieve full expansion [14]. The Atkinson cycle was realized with a complex linkage mechanism through a long expansion stroke and short intake and compression stroke [4]. The piston-type Atkinson cycle has the advantage of high thermal efficiency with the penalty of reduced power density and increased complexity [4]. However, the realistic Atkinson cycle cannot operate as full expansion process because the low in-cylinder pressure at the end of expansion stroke will lead to large exhaust pumping loss [15, 16]. Therefore the thermodynamic cycle of the real Atkinson engine is closer to Miller cycle engine rather than the original proposed full expansion cycle engine.

The concept of full expansion cycle also exists in gas turbine engines The definition of Humphrey cycle engine is mainly used for aviation application [17, 18]. The Humphrey cycle is a thermodynamic cycle modified from Brayton cycle and similar to pulse detonation engine [19]. The only difference between the Humphrey and Brayton cycle is the heat supply (combustion) process, in which Humphrey cycle adopts the heat through constant volume combustion rather than constant pressure combustion in Brayton cycle. Heiser and Pratt reported the comparative study of pulse detonation, Humphrey and Brayton cycles [19]. They concluded under the same operating conditions the thermal efficiency of Humphrey cycle was just slightly less than the pulse detonation cycle and when considering the realistic component process efficiencies it has comparatively high potential to achieve better performance than the real pulse detonation engine [19]. The majority of reported studies on the Humphrey cycle are mainly focusing on the application for large-scale system using gas turbine as the main component in aviation. It can be expected the utilisation of full expansion cycle can clearly benefit the small-scale power generation systems by high potential of improving the overall thermal efficiency.

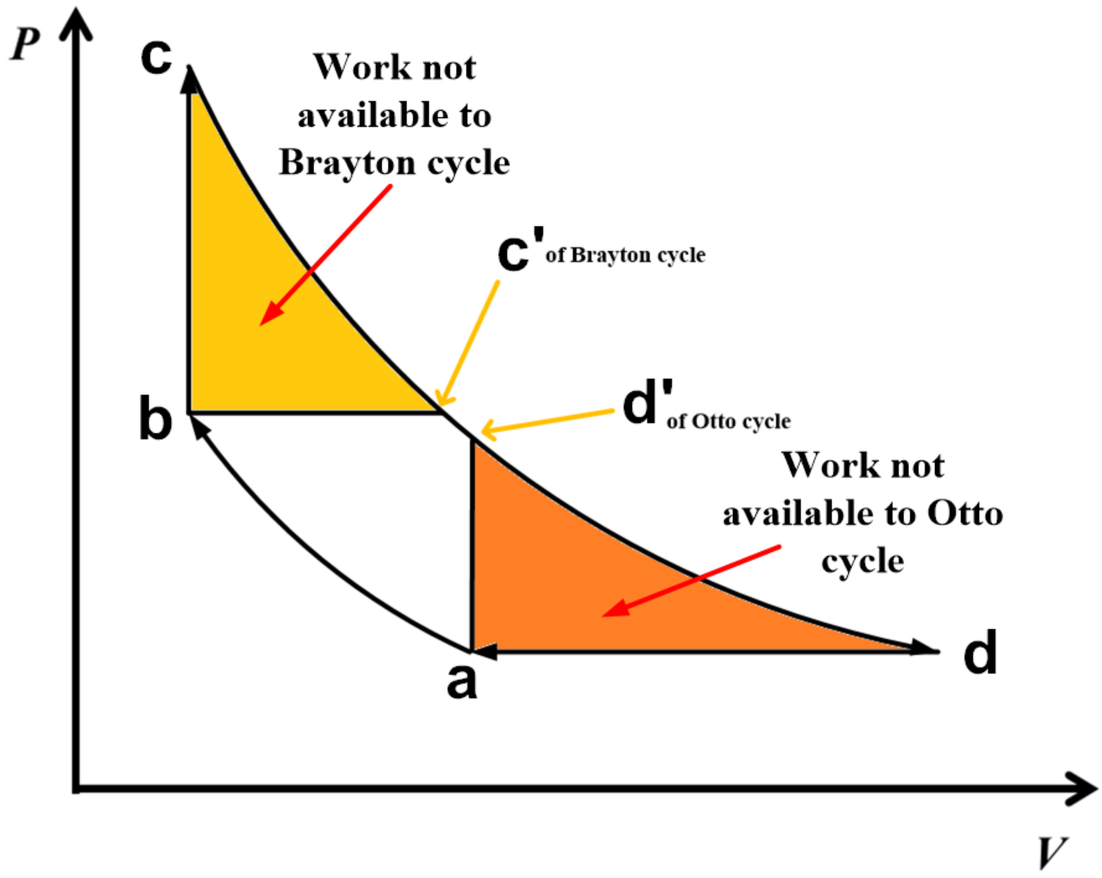


Fig. 1. P-V diagram of (1) a-b-c-d Humphrey cycle; (2) a-b-c′-d Brayton cycle; (3) a-b-c-d′ Otto cycle

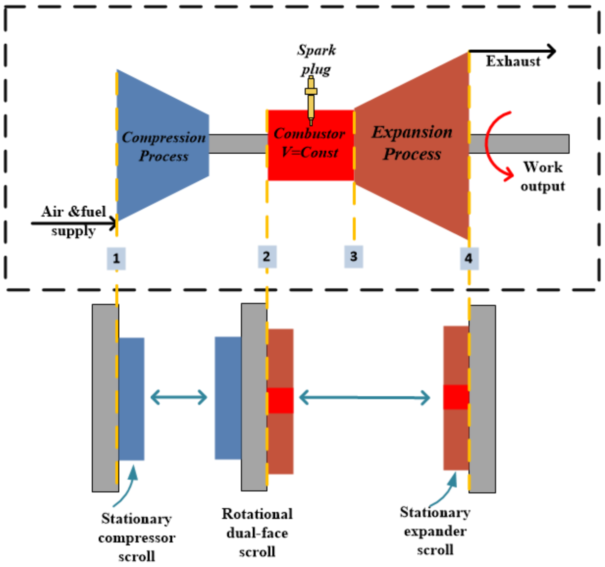
1.2 Compressor-expander device for small-scale Humphrey cycle engine

As previously described, the gas turbine technologies are normally used for large-scale application such as industrial power generation plant and aviation engine [8, 10]. The turbines normally are not recommended to be used to produce power less than 50 kW because of the high manufacture cost, their high rotational speed and poor performance for small-scale application [20]. For example, Habib et al. [21] reported the experimental investigation of a 30 kW small-scale gas turbine engine located in the Propulsion Laboratory of the University of Oklahoma. The tested gas turbine was a simple cycle machine without regeneration. The thermal efficiency of the tested gas turbine engine could only achieve averagely 5%, which is much lower than large-scale gas turbine engine [21].

The volumetric device such as vane, screw and scroll type compressor/expander has been widely used in small-scale power generation systems [20] and therefore can potentially form the small-scale Humphrey engine. The physical designs of vane [22] or screw [23] type expanders cannot form a serial system by simply connect the compressor/expander device in series [24]. In order to form the working principle of Humphrey cycle engine, the constant volume combustion is important to achieve. Scroll type machine has been widely used in small-scale power generation systems such as organic Rankine cycle [25-27] and advanced cogeneration cycles [28, 29] due to its advantages of compact size, low operation noise, high efficiency and low cost. The concept of the utilisation of scroll compressor-expander unit was introduced by Morishita et al [30] in 1992. The proposed scroll engine was a spark-ignition Otto cycle engine and limited valuable scientific results had been reported in the conference paper [30]. Kim et al. [31] reported the conceptual design of scroll expander-compressor unit to form a Stirling engine recovering solar energy. The proposed system had an estimated output power at 10.9 kW with the overall efficiency at 7.3% [31]. The scroll expander-compressor unit can also be used as a small-scale refrigerator, when the compressor side is driven by a motor [32, 33] or it can be used to compress the refrigerant to further higher pressure after the main compressor [34, 35]. The reviewed previous studies on scroll expander-compressor unit have confirmed the possibility to use the scroll type device forming a small-scale power generation system [32, 33]. However, the potential application of scroll expander-compressor unit as an ICE to perform the full expansion cycle, which can maximise the combustion energy, still need further investigations.

This paper aims to conduct a feasibility study of a scroll-type rotary ICE, who can potentially achieve the thermodynamic cycle-Humphrey cycle. The proposed system adopts full expansion process similar to the gas turbine engine and can be potentially used to burn gasoline under much lower compression ratio compared with the typical gasoline engine. The working principle of the scroll-type rotary ICE has been detailed introduced. First and second law analysis methods have been adopted to evaluate the thermodynamic performance of the scroll-type rotary engine and identify the optimal engine performance under different designed compression/expansion ratio. Moreover, the performance of small-scale scroll-type rotary ICE has been studied under the optimal compression/expansion ratio. And the Brake Specific Fuel Consumption (BSFC) of the proposed engine compared with conventional gasoline engine under the same operational conditions.

2. Description of the Scroll-type rotary Internal Combustion Engine



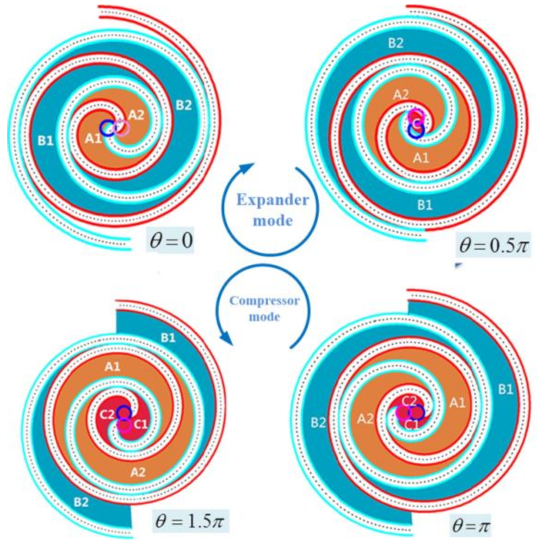


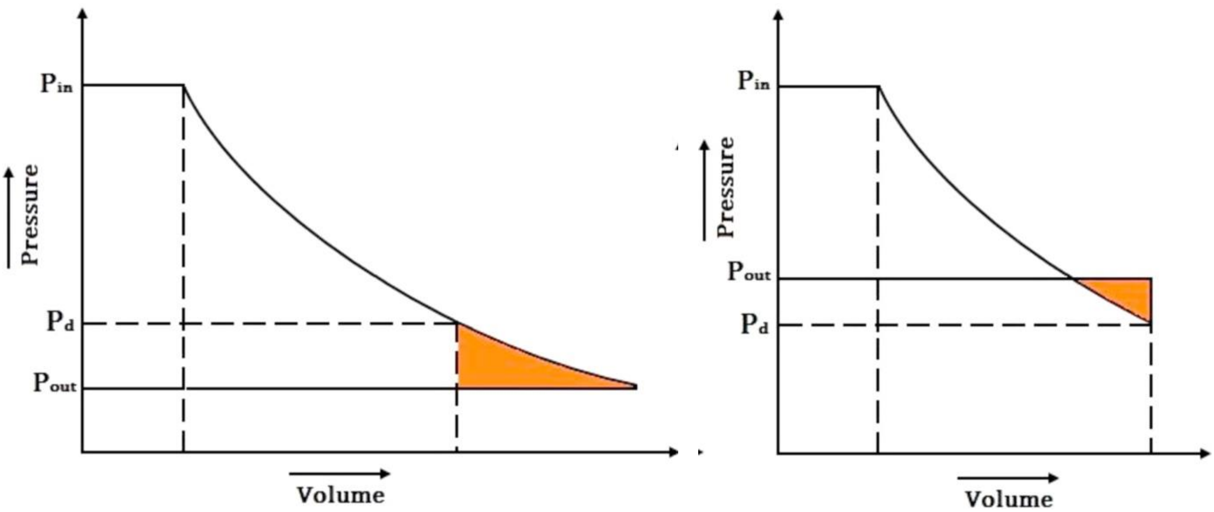
Fig. 2. Schematic diagram of scroll-type rotary ICE

Fig. 3. Working principle of scroll device under expander and compressor mode

Fig. 2 shows the schematic diagram of the scroll-type rotary ICE. The working process can be described as follows. From pint 1 to 2, the air and fuel mixture is supplied to the compressor part of the engine. The rotational dual-face scroll starts to rotate and compress the mixture from the suction area to the centre of the two scrolls in order to form the high pressured mixture as illustrated in Fig.3 compressor mode. The compressed air and fuel mixture flows through the centre port of the rotational dual-face scroll from the compressor side to the expander side. The combustion process happens in the chamber of the expander side of the engine as illustrated in Fig. 2. The mixture of high pressure air and fuel is ignited by the spark plug when the two chambers A1 and A2 finish the suction process as shown in Fig. 3 under the crank angle $\theta = 0$. Due to the combustion process is ignited in two fixed chamber, this process can be recognised as the constant volume combustion. Therefore the working process from Point 2 to 3 can be drawn as shown in Fig. 5. The pressures at the start and end points of the combustors are related to the geometric design of the scroll device. After the combustion process, the expansion process immediately starts, which is illustrated as the expander mode in Fig. 3. The high temperature/high pressure gases drive the expander part of the scroll-type rotary ICE. The work produced from the ICE is obtained from the shaft connected to the rotational dual-face scroll. The exhaust gases from the ICE are released direct to the environment at the exhaust port of the expander side of the engine, which means full expansion process can be obtained.

3. Thermodynamic analysis methods

Firstly, the ideal thermal energy efficiency of Humphrey cycle, Otto cycle and Brayton cycle has been studied and compared in this study to illustrate the performance and overall advantage of using full expansion cycle. The calculation conducted in this part sets the average combustion temperature at 1600 ºC and the environmental temperature at 30 ºC. The working fluid has been recognised as the ideal gas. The effects of exhaust gases and chemical reaction processes burning fossil fuel are not considered in this part of the calculation.



(a) (b)

Fig. 4. Under (a) and over (b) expansion losses [36]

The scroll-type device is a positive displacement machine, which has a fixed built-in volume ratio. The best performance of positive displacement machine can be achieved at the designed or built-in volume ratio [20]. Fig. 4 presents the schematic p-v diagrams of positive displacement machine operating in expansion mode. When the internal volume ratio is lower than the built-in volume ratio of the machine, under expansion will take place as shown in Fig. 4 (a). And the over expansion exists when the internal volume ratio is higher than the built-in volume ratio as illustrated in Fig. 4 (b). The losses during under and over expansion processes are illustrated as the yellow area in Fig. 4.

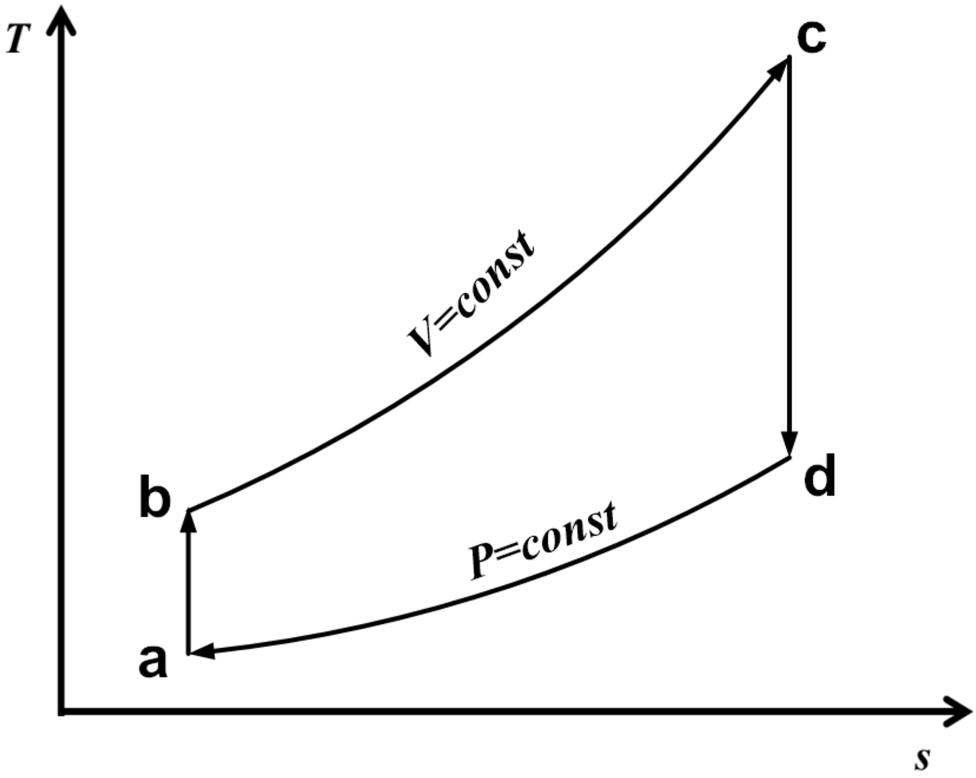


Fig. 5. T-s diagram of the scroll-type rotary Internal Combustion Engine

The second part of this work has been conducted to evaluate the effects of geometric relationship on the scroll-type rotary ICE overall performance. The thermal process of the scroll-type rotary Internal Combustion Engine can be indicated in the T-s diagram as illustrated in Fig. 5 and the schematic diagram of the system can be found in Fig. 2. Opposite to the working principle of under and over expansion losses as previously described, the over and under compression phenomenon also appear when the displacement device operating as compression mode [37]. Therefore the work consumed by the compression process of the scroll-type rotary engine can be calculated by Eq. (1), where $\dot{W}_{com\_ise}$ represents the isentropic compression work and $\dot{W}_{com\_iso}$ is the isochoric compression work.

$$\dot{W}_{com} = \underbrace{\dot{m} \times (h_{2\_d} - h_1)}_{\dot{W}_{com\_ise}} + \underbrace{\dot{m} \times (P_2 - P_{2\_d}) \times v_{2\_d}}_{\dot{W}_{com\_iso}} = \dot{m} \times (h_2 - h_1) \tag{1}$$

Point 2_d is the designed working point defined by the geometric parameter of the scrolls under isentropic expansion process, which can be calculated by the specific volume v_{2_d} and entropy s_{2_d} as shown in Eq. (2). $\gamma_{\_\mathrm{com}}$ is the built-in compression volume ratio of the scroll-type engine from working point 1 to point 2.

$$v_{2\_d} = \frac{v_{\_1}}{\gamma_{\_\mathrm{com}}} \tag{2}$$

$$s_{2\_d} = s_1 \tag{3}$$

The discharged pressure condition P_2 is defined by Eq. (4), where h_2 can be calculated from Eq. (1) and v_2 is defined as 90% of v_{2_d} because the volumetric efficiency is suggested around 0.9 based on experimental data as reported by Navarro et al. [38].

$$P_2 = f(h_2, v_2) \tag{4}$$

The combustion process is assumed as constant volume combustion as illustrated as Process 2-3 in Fig. 5. The energy provided to the engine during combustion process is calculated by the following equations, where assumes 80% of overall fuel energy can be obtained by the engine. ($\eta_{2-3} = 0.8$)

$$\dot{Q}_{combustion} = \frac{\dot{m} \times (h_3 - h_2)}{\eta_{2-3}} \tag{5}$$

$$h_3 = f(T_3, v_3) \tag{6}$$

As a volumetric device, the work produced from the expander side of the engine consists of isentropic expansion work and isochoric expansion work. Therefore, the work generated from the expander side of the engine can be calculated by Eq. (7), where h_{4_d} is the exhaust specific enthalpy of after the isentropic expansion process.

$$\dot{W}_{\exp} = \underbrace{\dot{m} \times (h_3 - h_{4\_d})}_{\dot{W}_{\exp\_ise}} + \underbrace{\dot{m} \times (P_{4\_d} - P_1) \times v_{4\_d}}_{\dot{W}_{\exp\_iso}} = \dot{m} \times (h_3 - h_4) \tag{7}$$

The working conditions of Point 4_d can be calculated by the specific volume v_{4_d} and entropy s_{4_d} as illustrated in Eq. (8), where $\gamma_{\_\exp}$ is the built-in expansion volume ratio of the scroll-type engine from working point 3 to point 4.

$$v_{4\_d} = \frac{v_{\_3}}{\gamma_{\_\exp}} \tag{8}$$

$$s_{4\_d} = s_3 \tag{9}$$

The overall thermal efficiency of the scroll-type rotary engine can therefore be defined as

$$\eta_{I\_scroll\_ICE} = \frac{\dot{W}_{\exp} - \dot{W}_{com}}{\dot{Q}_{combustion}} \tag{10}$$

The second law analysis method is adopted in this study to evaluate the maximum available work from the system. The calculation of the exergy flow per unit time of different operating point can be defined as Eq. (11).

$$\dot{\mathrm{E}}_i = \dot{m} \times [(h_i - h_0) - T_0 \times (s_i - s_0)] \tag{11}$$

Therefore the exergy efficiency of the scroll-type rotary ICE can be calculated by the following equation.

$$\eta_{\mathrm{II}\_scroll\_ICE} = \frac{\dot{W}_{\exp} - \dot{W}_{com}}{\dot{\mathrm{E}}_{combustion}} = \frac{\dot{W}_{\exp} - \dot{W}_{com}}{\dot{\mathrm{E}}_3 - \dot{\mathrm{E}}_2} \tag{12}$$

The mass flow rate of the intake air can be calculated by the volumetric flow rate of the suction air divided by the specific volume of the inlet air as displayed as Eq. (13), where $V_{combustion}$ is the combustion volume of the scroll rotary ICE per turn and N is the rotational speed.

$$\dot{m}_{inlet\_air} = \frac{\dot{V}_{inlet\_air}}{v_1} = \frac{N}{60} \times \frac{V_{combustion}}{v_3} \tag{13}$$

The formula of isooctane can be recognised as the average chemical formula for gasoline, which can be written as C_8H_{18} [39]. The chemical reaction equation of the combustion process can therefore be represented as Eq. (14).

$$C_8H_{18} + 12.5(O_2 + 3.76N_2) \longrightarrow 8CO_2 + 9H_2O + 47N_2 \tag{14}$$

The mass flow rate of the fuel supplied to the scroll-type rotary engine can therefore be defined as the following equation, where the molecular mass of C_8H_{18}, O_2 and N_2 are respectively represented as $M_{C_8H_{18}}$, M_{O_2} and M_{N_2}.

$$\dot{m}_{fuel} = \dot{m}_{inlet\_air} \times \frac{M_{C_8H_{18}}}{12.5\left(M_{O_2} + 3.76M_{N_2}\right)} \tag{15}$$

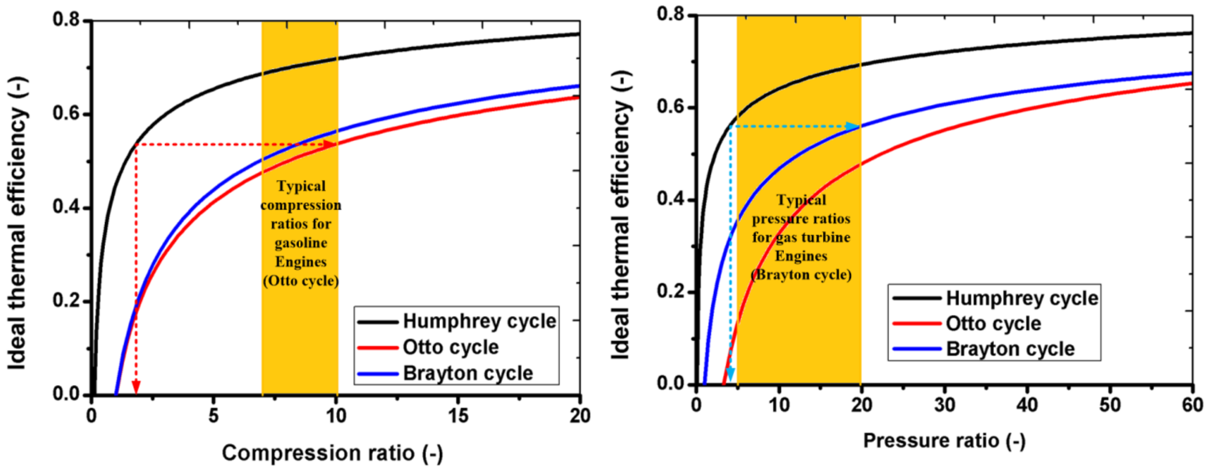
The Brake Specific Fuel Consumption of the scroll-type rotary engine can be written as Eq. (16).

$$BSFC = \frac{\dot{m}_{fuel}}{\dot{W}_{\exp} - \dot{W}_{com}} \tag{16}$$

4. Results and discussion

4.1 Performance comparison of Humphrey, Otto and Brayton cycle

The scroll-type rotary ICE adopts Humphrey cycle throughout the operations as previously described. The ideal thermal efficiency of the Humphrey cycle, Otto cycle (gasoline engine) and Brayton cycle (gas turbine engine) under different compression and pressure ratio has been studied and compared. In order to avoid misfire, the compression ratio of a typical gasoline engine ranges from 7:1 to 10:1, which limits the overall thermal efficiency within the highlighted area as shown in Fig. 6 (a). The maximum ideal thermal efficiency of a gasoline engine under 10:1 compression ratio is about 0.55, which can be achieved by gas turbine engine using Brayton cycle under around 8:1 compression ratio. On the other hand, the novel scroll-type rotary Internal Combustion Engine using Humphrey cycle only requires the compression ratio as low as 2.05 to achieve the same overall thermal efficiency of the Otto cycle under the maximum compression ratio.



(a) (b)

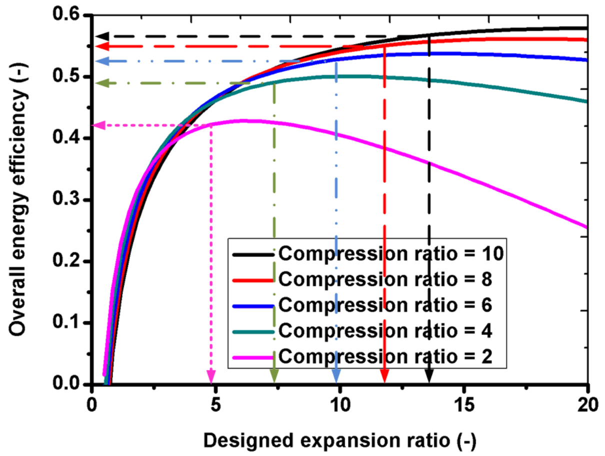
Fig. 6. Comparison of ideal thermal efficiency of Humphrey cycle, Otto cycle and Brayton cycle

(a) under different compression ratio, (b) under different pressure ratio

Typical gas turbine engines can be operated under the pressure ratio from 5 to 20 as the highlighted area in Fig. 6 (b), which illustrates the theoretical overall thermal efficiency of the gas turbine engine can always be higher than that of the gasoline engine under the same pressure ratio. Results pointed out the maximum thermal efficiency of Brayton cycle within the operational conditions of the typical gas turbine under pressure ratio at 20:1 is about 0.56, which can be achieved by the Humphrey cycle under the pressure ratio at 4.1. The results clearly presented under the same designed operational conditions the performance of Humphrey cycle is far better than that of Otto cycle and Brayton cycle. Moreover, the scroll-type rotary ICE adopting Humphrey cycle can achieve the same overall thermal efficiency as that of typical gasoline engine and gas turbine engine under relatively low compression and pressure ratio, which means the cost of material used in the scroll-type rotary Internal Combustion Engine can be much lower than that of typical gasoline engine and gas turbine engine.

4.2 Evaluation of energy and exergy efficiency of the scroll-type rotary engine under different designed compressor compression ratio

Other than piston type ICE, the scroll-type ICE can be operated using different volume compression/expansion ratio during the compression and expansion processes. The effects of variable compression/expansion ratio of the compressor/expander side of the scroll-type rotary ICE have been studied. Five compression ratios of the compressor side are selected to investigate the influence of changing expansion ratio on the performance of the engine. Results indicate the optimal overall energy efficiency of the scroll-type rotary engine exist within the engine compression ratio from 2:1 to 10:1. Due to the complicity for the design and difficulty manufacture for high expansion ratio scroll device, the desirable compression/expansion ratio relationship can be identified through the analysis of the system energy efficiency as shown in Fig. 7. The identified compression/expansion ratio of the scroll-type rotary engine can achieve very close to the maximum energy efficiency of the system as the lines illustrated in Fig. 7. At the optimal performance point, the designed expansion ratio of expander side is much higher than the compression ratio of compressor side, which meets the design working principle of the full expansion cycle. Fig. 7 shows the identified compression/expansion ratios are 2:1/4.8:1, 4:1/7.4:1, 6:1/9.9:1, 8:1/11.8:1 and 10:1/14.1:1, when the energy efficiency of the system can be respectively achieved at 42.22 %, 49.13 %, 52.82 %, 55.08 % and 56.96 %.



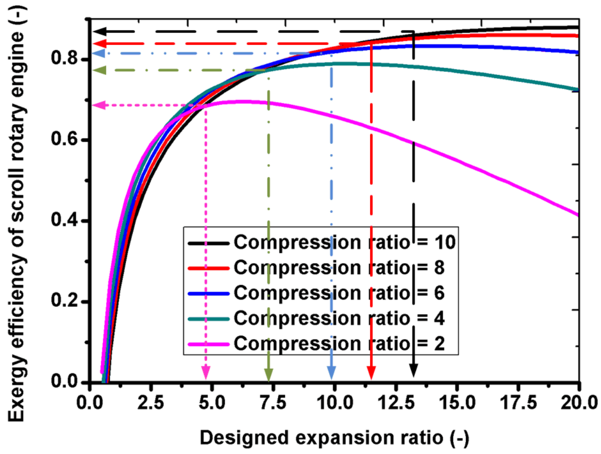


Fig. 7. Energy efficiency of the scroll-type rotary Internal Combustion Engine

Fig. 8. Exergy efficiency of the scroll-type rotary Internal Combustion Engine

The exergy analysis method has been used to analyse the maximum availability of the power generation system and the results can also be used to validate the reliability of the identified compression/expansion ratios of the scroll-type rotary engine as previously discussed. The results of the exergy efficiency of the system are plotted in Fig. 8. The exergy efficiency of the system has a similar tendency as the results presented in Fig. 7 using the first law analysis. Results show under the identified compression/expansion ratios 2:1/4.8:1, 4:1/7.4:1, 6:1/9.9:1, 8:1/11.8:1 and 10:1/14.1:1, the system exergy efficiency can be respectively achieved at 68.59 %, 77.46 %, 81.89 %, 84.38% and 86.44 %.

4.3 Evaluation of small-scale scroll-type rotary Internal Combustion Engine under identified compression/expansion ratio

A case study has been conducted in order to predict the performance of the scroll-type ICE. Due to the fact that scroll device is more suitable to be used for small-scale application, the case study conducted in this part has set the combustion volume of the scroll engine at 35 cm^3. And the rotational speed of the engine has been selected and fixed at 3000 rpm in the calculation because the selected speed is favourable to be used for scroll device and the engine can be directly connected to conventional electricity generator under the designed rotational speed. The compression/expansion ratio of the small scroll engine has been set at the identified parameters as obtained in the previous section. The effective power, fuel energy input, compressor power and dumped energy from the exhaust of the small-scale scroll-type rotary engine under the designed geometric parameters are drawn in Fig. 9. The effective power generated from the engine under the designed compression ratio at 2:1, 4:1, 6:1, 8:1 and 10:1 is respectively 3.343, 7.343, 11.34, 15.19 and 19.01 kW. With the increase of compression ratio, the power consumed by the compression process of the engine occupies more of the overall fuel energy, which can be observed in Fig. 9. The results also suggest under relative low designed compression ratio such as 2:1, 4:1 and 6:1, the potential recovery of engine exhaust energy can potentially be used to cover the energy demand of compression process and boost the engine performance. When the designed compression ratio of the scroll-type rotary engine is 8:1 and 10:1, the exhaust energy only occupies 7.27 % and 4.15 % of the overall fuel input energy, which means under high designed compression ratio, the recovery of exhaust energy to improve the engine performance is quite limited and therefore is not recommended.

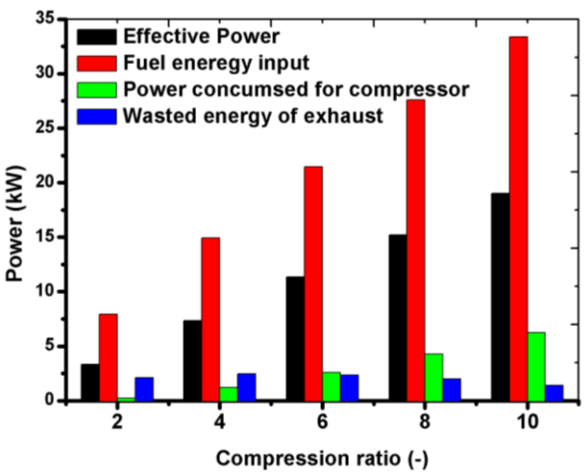


Fig. 9. The ratio of overall energy under different identified compression/expansion ratio

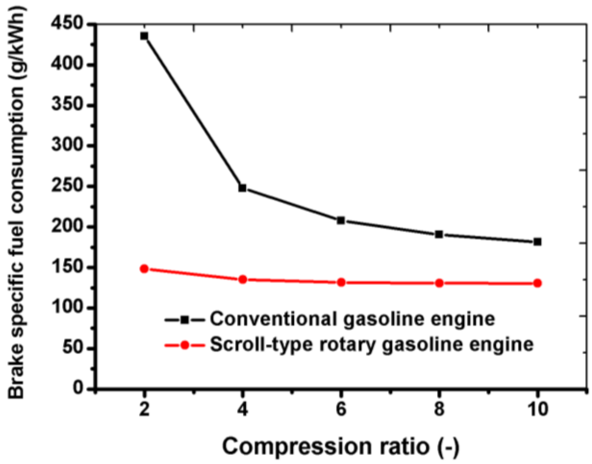


Fig. 10. BSFC performance of scroll-type rotary and conventional gasoline engine

As one of the most important parameters to evaluate the engine performance, BSFC can illustrate the fuel efficiency of ICE. The calculation method for the BSFC of the scroll-type rotary ICE can be found in Eq. (16) as previously introduced. Comparison of the BSFC of the scroll-type engine burning gasoline and that of the conventional gasoline engine under the same operational conditions have been conducted. The results are plotted in Fig. 10. Results indicate the BSFC of the scroll-type gasoline engine under the identified compression/expansion ratio ranges from 148.5 to 130.5 g/kWh, which is much lower than that of the conventional gasoline engine. When the compression ratio of the engine is set at 2:1 and 10:1, the BSFC of scroll-type rotary ICE can respectively improve the fuel efficiency by 65.89 % and 28.02 %.

5. Conclusions

In this study, a scroll-type rotary gasoline Internal Combustion Engine using advanced power generation cycle (Humphrey Cycle) has been proposed and studied. The ideal thermal efficiency of the Humphrey cycle, Otto cycle (gasoline engine) and Brayton cycle (gas turbine engine) under different compression and pressure ratio has been studied and compared. Results indicate under the same designed operational conditions the performance of Humphrey cycle is far better than that of Otto cycle and Brayton cycle, which means scroll-type rotary ICE adopting Humphrey cycle can achieve the same overall thermal efficiency as that of the typical gasoline engine and gas turbine engine under relatively low compression and pressure ratio.

The effects of variable compression/expansion ratio of the compressor/expander side of the scroll-type rotary ICE have then been studied. And results show the optimal performance can be achieved under the compression/expansion ratio at 2:1/4.8:1, 4:1/7.4:1, 6:1/9.9:1, 8:1/11.8:1 and 10:1/14.1:1, when the energy efficiency of the system can be respectively achieved at 42.22 %, 49.13 %, 52.82 %, 55.08 % and 56.96 %. And the exergy efficiency of the novel engine can be respectively achieved at 68.59 %, 77.46 %, 81.89 %, 84.38% and 86.44 %. A case study has been conducted to predict the performance of the novel scroll-type rotary ICE with fixed combustion volume at 35 cm^3. When the rotational speed of the engine at 3000 rpm, results indicate under designed compression ratio from 2:1 to 10:1 the effective power from the system ranges from 3.343 to 19.01 kW. The fuel consumption of the scroll-type rotary engine burning gasoline has also been evaluated and the results are compared with that of the conventional gasoline engine under the same operational conditions. Results indicate the BSFC of scroll-type rotary gasoline engine ranges from 130.5 to 148.5 g/kWh under the identified compression/expansion ratio, which improves the fuel efficiency by 28.02 % and 65.89 % compared to that of the conventional gasoline engine. The proposed scroll-type rotary engine has advantages of compact size and high overall energy efficiency, which has potential to be used as the auxiliary power unit of range extender vehicle or for motorcycle application.

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